Photon Spin, Zero-point Energy and Black-body Radiation

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Abstract

A critical review of the obscure nature of the contribution of spin energy to the energy of the electromagnetic field is presented. It is proposed that the total energy of a photon $h\nu$ comprises of kinetic and spin parts each equal to $h\nu/2$. Classical magnetic field is reinterpreted as angular momentum flux of photon fluid. The black-body radiation law is revisited in the light of new significance of the zero-point energy proposed here.

1 Introduction

Planck's law for black-body radiation spectrum presented on 19 October, 1900 before the German Physical Society marks the beginning of the quantum era: the defining elements of the first quantum theory of radiation are Planck's assumption that simple Hertzian oscillators of radiation possess discrete energy, the result that the average energy of an oscillator of frequency ν is an integral multiple of $h\nu$, and the assumption that the smallest unit of energy exchanged between matter and radiation is $h\nu$. Planck's constant h is, similar to the Boltzmann constant k, a constant of nature. It was only in 1924 that a satisfactory derivation of Planck's law based on purely quantum nature of radiation was given by Bose. The new statistics proposed by Bose

for photon gas was immediately applied by Einstein to the ideal gas of matter and it has come to be known as Bose-Einstein statistics. A nice historical review is given by Whittaker [1]. Most of the modern textbooks of quantum theory and quantum optics briefly mention the historical significance of the Planck's law in the so called quantum revolution, and tend to overlook the conceptual problems which were faced by Planck and Einstein in reconciling the light quantum hypothesis with the classical electromagnetic field theory. Physical reality of light quantum (named photon by Lewis in 1926) and its properties were uncertain during most of the period when the foundations of quantum theory were laid, therefore it is not only instructive to get acquainted with the struggle that preceded the development of wave mechanics and matrix mechanics but also rewarding to explore the possibility of reviving some of the old ideas for resolving contemporary issues. Post offers a significant critique on the Copenhagen interpretation of quantum mechanics [2] highlighting the fact that the presumably typical quantum result i.e. the zero-point energy was introduced first by Planck for an ensemble of phase randomized oscillators. Post's monograph also made me aware of the ingenious approach to the black-body radiation law initiated by Boyer in 1969 [3]. Though the mainstream physics has largely ignored such efforts it would have been natural to expect that in the light of single photon experiments and advances in quantum optics there would be a renewed interest in such fundamental questions. Contrary to the prevalent scenario in which quantum mysteries are supposedly serving as a resource for quantum information science, a critical review [4] has led me to the conclusion that even today we do not have a clear and unambiguous answer to the question: What is photon? In the process of trying to understand this question a startling fact has emerged: photon spin angular momentum has played no role in the derivation of Planck's law excepting, of course, the passive polarization state counting in the derivation of Bose. In the present article an attempt is made to gain new insights into the black-body radiation physics considering the spin of photon.

It is universally recognized that Planck introduced the quantum of radiation energy, however equally important was his use of entropy in the problem of black-body radiation [1]. It is worth mentioning that earlier Boltzmann proved the empirically established Stefan's law using classical radiation theory and second law of thermodynamics. Imprint of Planck's approach can be found in several derivations given by Einstein in which entropy played a crucial role; Knight and Allen [5] give a succinct review of Einsteins at-

tempts beginning with his 1905 paper on photoelectric effect, and also reprint the English translation of his 1917 paper. In the photoelectric effect paper Einstein drew analogy between the entropy change for an ideal gas whose volume is varied isothermally and the similar change in entropy of radiation satisfying the Wien's law: this suggested that in the high frequency limit the radiation has corpuscular nature. The calculation of energy fluctuation for the black-body radiation using Planck's law in 1909 showed that large wavelength radiation had wave nature while in high frequency limit the radiation showed particulate aspects: this was the first enunciation of wave-particle duality for the radiation. The hypothesis of spontaneous and stimulated emission of radiation was put forward by Einstein in the important paper of 1917; it is interesting that immediately after his struggle to obtain the field equation for gravitation ended in 1915 he returned to the problem of light quanta. The existence of radiation pressure was known since the time of Maxwell, but directed momentum for photon and the exchange of momentum between radiation and matter during the interaction process appeared for the first time in this paper. It is noteworthy that Bohr's quantum theory of atomic spectra and classical theory of Doppler effect both were used by Einstein in this paper.

A little known but important fact is that Planck himself was unwilling to discard classical theory of Maxwell, and in 1911 proposed a new hypothesis: radiation behaves as a classical wave in free space while emission process is discontinuous. In Planck's second theory the average energy is in excess by the amount of $h\nu/2$ at all temperatures to the one corresponding to the Planck's law, and at absolute temperature zero, the oscillator has average energy of $h\nu/2$. The zero point energy associated with quantum vacuum fluctuations represents a typical counter-intuitive feature of modern quantum field theories, and has observational implications like Lamb shift and Casimir force. Whittakar, Post and Boyer in their own way have rightly emphasized its origin in the work of Planck. Boyer draws attention to the papers of Einstein and Hopf (1910) in which equipartition of energy in classical theory led to the Rayleigh-Jeans law. Following Einstein-Hopf approach, questioning the equipartition theorem of energy and introducing an additional hypothesis of a Lorentz-invariant spectrum of zero-point classical radiation Boyer [3] arrives at the Planck's law. Whittaker notes that Einstein and Stern in 1913 derived the Planck's law using zero-point radiation.. It seems this work has escaped the attention of Boyer; it would be of interest to know its details.

The landmark paper of Bose (1924) had essentially three new ingredients:

the statistics assuming indistinguishability of photons in the photon gas, partitioning of phase space into the finite-sized (of size h^3) discrete cells, and the use of two polarization states for photon. Note that besides these Bose held total energy fixed while number of photons was not conserved. The third ingredient in the Bose's derivation has not received adequate attention; it is unfortunate that Pais [6] considers the derivation given by Bose as 'a successful shot in the dark', and remarks that the factor of 2 for polarization counting was done with slight hesitation. Ramaseshan has placed on record reflections of Bose on this issue [7], and quoted from 1931 paper of Raman and Bhagawantam suggesting that (contrary to the views of Pais) Bose had even anticipated the spin angular momentum for photon of value $\pm\hbar$. Here $\hbar$ is $h/2\pi$. Einstein appears to have been in an unsure state of mind on the role of angular momentum in quantum theory; in this regard Pais quotes a letter written by Einstein to P. Ehrenfest in 1926. I have critically reviewed some of these aspects in Chapter 5 of the monograph [8]. I think a fairly reasonable conclusion can be drawn: unlike the key role of linear momentum of photon, the spin has been assigned a passive role in the derivation of Planck's law in spite of the fact that black-body radiation is unpolarized.

Recently it dawned on me that both for photon and classical radiation the energy associated with spin or rotation has remained obscure. In [4] a radical revision of the interpretation of classical electrodynamics has been suggested: electromagnetic field tensor itself represents the angular momentum tensor of photon fluid. Concerning the single photon it is argued that simple oscillator model cannot take into account spin, and a new hypothesis is put forward: total energy $h\nu$ is equally divided into its translational energy (corresponding to momentum $h\nu/c$) and rotational energy (for spin $\hbar$) endowing a new significance to the zero-point energy $h\nu/2$. Some considerations of photon model can be found in [9] and its application to understand Doppler effect is given in [10]. In the next section the problem of energy associated with spin is elucidated, and a possible resolution is discussed in Sec. 3. Derivation of Planck's law is approached afresh in the light of these considerations in Sec. 4, and concluding remarks constitute the last section.

2 Spin and Energy

Energy, momentum and angular momentum of the electromagnetic field and the conservation laws are well known, and find standard treatment in the

textbooks. Starting from the Maxwell field equations or using the symmetry principles in the action integral and associated Noether currents one arrives at these conservation laws, see e.g. Jackson's book [11]. In this section certain salient features related with the conceptual problems are highlighted. To fix the notation, in relativistic formulation Greek indices run from 0 to 3 while x^0 is ct, and Latin indices run from 1 to 3; four-volume element is $d\tau (= dx^0 dx^1 dx^2 dx^3)$, and space volume is dV. The Lagrangian density for the electromagnetic field is given by

$$L = -(1/16\pi) F^{\mu\nu} F_{\mu\nu} \tag{1}$$

Here the electromagnetic field tensor

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \tag{2}$$

The action

$$I = \int L d\tau \tag{3}$$

is a Lorentz-invariant scalar, and the infinitesimal coordinate translation x^μ to $x^\mu + \delta x^\mu$ leads to the covariant conservation law for the canonical energy-momentum tensor $T^{\mu\nu}$. Note that we are considering source free electromagnetic field in vacuum. It is somewhat disconcerting to find that T^{00} and T^{0i} differ from the usual standard expressions for energy-density and momentum-density respectively given by

$$u = (\mathbf{E}^2 + \mathbf{B}^2)/8\pi \tag{4}$$

$$\mathbf{g} = (\mathbf{E} \times \mathbf{B})/4\pi c \tag{5}$$

Integrating over all space the additional terms in T^{00} and T^{0i} give no contribution being divergence terms which are transformed to the vanishing surface integrals. Here volume integrated u and $\mathbf{g}$ transform as energy-momentum four-vector p^μ.

The canonical tensor suffers from two other formal defects: it is not symmetric, and is not gauge invariant. Rotational invariance, in general, ensures angular momentum conservation. If we construct angular momentum density from canonical tensor

$$M^{\mu\nu\lambda} = T^{\mu\nu} x^\lambda - T^{\mu\lambda} x^\nu \tag{6}$$

then it is not conserved. It is possible to derive a symmetric, traceless and gauge invariant energy-momentum tensor. $E^{\mu\nu}$ such that

$$E^{\mu\nu} = T^{\mu\nu} + t^{\mu\nu} \tag{7}$$

Here $t^{\mu\nu}$ is divergenceless spin energy momentum tensor that ensures angular momentum conservation. Interestingly $t^{\mu\nu}$ does not contribute to the total energy and momentum of the field since

$$\int E^{\mu 0} dV = \int T^{\mu 0} dV \tag{8}$$

Like $T^{\mu\nu}$ the spin energy-momentum tensor is also not gauge invariant, for example,

$$t_{\mu\nu} = \partial^{\lambda} A_{\mu} F_{\nu\lambda} \tag{9}$$

Let us construct angular momentum tensor from the symmetric tensor

$$A_{\lambda\mu\nu} = x_{\lambda} E_{\mu\nu} - x_{\mu} E_{\lambda\nu} \tag{10}$$

This differs from the angular momentum tensor $J_{\lambda\mu\nu}$ obtained from the infinitesimal Lorentz rotation invariance of the action I, however the distinction is unimportant since the difference between the two is a pure divergence term and the volume integrated angular momentum for both is identically equal

$$\int A_{ij0} dV = \int J_{ij0} dV \tag{11}$$

It would be tempting to seek division of $J_{\lambda\mu\nu}$ (or $A_{\lambda\mu\nu}$) into orbital and spin parts; unfortunately for a massless vector field it is not possible to identify orbital and spin parts in a gauge invariant manner.

Corson in an illuminating monograph [12] presents detailed discussion on the formal aspects of field theories and symmetries. In the following the problem of energy associated with angular momentum is elucidated considering the examples of plane electromagnetic wave, photon and multipole radiation. The vectors **E** and **B** satisfy the wave equatrion which has plane wave solutions. The divergence equations in the set of Maxwell equations imply that **E** and **B** are both perpendicular to the direction of propagation, and the curl equations show that **E** and **B** are perpendicular to each other. The time-averaged energy density and momentum density calculated using the expressions (1) and (5) satisfy the simple relation

$$u = |\mathbf{g}| c \tag{12}$$

It is significant that this relation holds for a monochromatic plane wave in any state of polarization. Beth in 1936 [13] demonstrated experimentally that circularly polarized light carried angular momentum as suggested by Poynting; it is termed intrinsic spin angular momentum. Validity of the relation (12) independent of polarization seems to suggest that spin has no energy.

In a simplified picture photon with rest mass zero is believed to satisfy the energy-momentum equation given by

$$E = |\mathbf{p}|c \tag{13}$$

Note that it is analogues to Eq.(12) for plane wave. Making use of Planck's quantum hypothesis for energy $h\nu$ we can interpret photon momentum to be $h\nu$/c or

$$\mathbf{p} = \hbar\mathbf{k} \tag{14}$$

Though photon carries spin of $\pm\hbar$, the energy of photon once again turns out to be independent of the spin angular momentum. In fact, in quantum optics the polarization property of light is described using a polarization index (s = 1,2) in the field operators, and introducing a unit polarization vector basis, see [14]. It can be proved that the spin angular momentum operator is diagonal in the basis of circular polarization in the number states of Fock space. For a plane light wave the spin is along the direction of propagation with the magnitude $\hbar$ times the difference between the number of right and left circularly polarized photons. Single photon state in a plane wave has momentum $\hbar\mathbf{k}$ and spin $\hbar$ along the direction of $\mathbf{k}$. What is the energy of the spinning photon? A clear statement on this question is given by Kompaneyets [15] on p.276: 'A quantum has one more, so to say, internal degreee of freedom, that of polarization. This peculiar degree of freedom corresponds to the "coordinate" σ, taking only two values $\sigma = 1$ and $\sigma = 2$. The energy does not depend upon σ'.

Following Jackson [11] we can represent the general solution of the Maxwell field equations in terms of the vector spherical harmonics $\mathbf{L}Y_{lm}$ where $\mathbf{L}$ is the orbital angular momentum operator and Y_{lm} is the spherical harmonics of order (l,m). Use is made of transverse electric and magnetic multipole fields. For the radiation field time-averaged energy density is calculated using Eq. (4) and the angular momentum density is calculated from the expression $\mathbf{r}\times\mathbf{g}$. We omit the details and note that in [11] the ratio of the z-component of the differential of angular momentum and energy in a spherical shell between

r and r + dr is shown to be m/ω. A quantum mechanical interpretation is indicated, 'the radiations from a multipole of order (l, m) carries off $m\hbar$ units of z-component of angular momentum per photon of energy $\hbar\omega$'. Such an assertion looks quite attractive, however closer scrutiny reveals that the fact that photon has intrinsic spin $\hbar$ and that the energy $\hbar\omega$ of a photon is due to its momentum $h\nu$/c in the standard picture make this result intriguing. What is the contribution of $m\hbar$ units of angular momentum to the energy of photon?

Let us recall that in classical rotational dynamics of a point particles or a rigid body the angular momentum for pure rotation is defined with reference to a rotation axis, and the conservation laws can be expressed with reference to inertial frame of reference. Rotational energy of a rigid body defined in terms of moment of inertia and angular momentum is essentially the kinetic energy of linear motion of the constituent mass points of the body. However, intrinsic spinning motion does not have this kind of simple picture. The role of angular momentum in total energy of the classical electromagnetic field is more complicated and obscure as noted above.

3 New Approach

It would be interesting to explore the possibility of developing a microscopic theory of electromagnetic fields in which one begins from the first principles using photon dynamics. In contrast numerous attempts since the advent of quantum theory have built photon picture from the quantization of the electromagnetic radiation, and face the conceptual problems of manifest Lorentz covariance, gauge invariance, localizability of photon, and physically meaningful photon wavefunction, see review in [4, 8, 9]. Kobe in a nice review [16] draws attention to a 1931 Oppenheimer's effort to develop a photon wave equation without the electromagnetic fields. Kobe's own approach is the second quantization of the Schroedinger form of equation obtained from the Maxwell field equations. He constructs momentum operator from a velocity operator and relativistic mass of photon that seems strange as momentum operator has to be fundamental in canonical quantization not the velocity operator. In our approach [4] we make a radical departure and argue that electric and magnetic fields are not fundamental, and these are macroscopic physical quantities describing an ensemble of large number of photons (some kind of a photon fluid). A truly microscopic foundation for electromagnetism

would be our ultimate goal; here we present some progress in this direction addressing the question of angular momentum and energy discussed in the preceding section.

Philosophical idea on which our approach is based endows physical reality to space (may be called aether!) and time is the cause of the manifest space and action itself [17]. Neutrino(s), electron and photon are envisaged to be the 'spatio-temporal' objects and their observable attributes have geometrical and topological origin. Spatial disturbances (vibration and rotation) represent the internal fields of the spatio-temporal objects. It is assumed that internal motion is in synchronization with the translational motion: the internal time (or frequency) is also the periodicity of the translation such that the configuration returns to its initial form. This synchronization establishes a sort of what could be termed as relativistic rigidity in view of the relationship between spatial extension and time periodicity, and the absence of any rest state. Let us confine to the case of photon that is postulated to be a physically real object. It has been argued in [4] that the electronic charge can be factored out from the Maxwell field equations rendering electromagnetic fields in purely geometrical units, for example, electric and magnetic fields have dimension of $(\text{length})^{-2}$. The Lorentz force expression, however becomes

$$Force = e^2[\mathbf{E} + (\mathbf{v} \times \mathbf{B})/c] \tag{15}$$

It is encouraging that it would be consistent with the approach in which e^2/c having the dimension of angular momentum is interpreted to give a mechanical significance to the electronic charge [8]. To represent a single photon we consider the vector potential divided by e and multiplied by $\hbar$

$$\mathbf{a} = \hbar\mathbf{A}/e \tag{16}$$

A crucial step is to treat the three degrees of freedom associated with $\mathbf{a}$ to define internal rotation (spin) and momentum of the photon. Note that $\mathbf{a}$ has the dimension of momentum. In the standard theory triad of unit vectors is often used to take into account helicity states and momentum of photon. Here two components of $\mathbf{a}$ determine spin and the third component represents the momentum of photon, for example, in the space-fixed reference frame z-axis may be assumed to be the direction of propagation. It appears that the natural mathematical language for the present approach is that of differential forms and cohomology. Post [2] and Kiehn [18] have alerted the physicists to the immense potential of de Rham cohomology for addressing fundamental

questions in physics. It may be mentioned that gauge field theories and superstrings have found differential forms and fibre bundles quite fruitful. We refer to Kiehn's paper [18] , Post's book [2] and Chapter 6 in [8] for physically motivated introduction to Cartan's exterior differential forms. In electromagnetism the vector potential can be written as a one-form $A_i dx^i$ in three-dimension, while in space-time the four-vector potential gives the one-form A ($= A_\mu dx^\mu$) and the electromagnetic field tensor is a two-form F = dA. Here the exterior derivative d transforms a p-form to a (p+1)-form; using Cartans wedge product of p-differentials and contracting p indices of an antisymmetric tensor we construct a p-form. Besides d, one defines its adjoint δ. In general a one-form A can be decomposed into three parts

$$A = d\alpha + \delta\beta + \gamma \tag{17}$$

The contribution from the harmonic component γ in the integral of A contains the topological property. Kiehn calls such integrals as period integrals.

We propose that the period integral of one-form a from Eq. (16) represents spin as a topological property of photon

$$\oint a = \hbar \tag{18}$$

It is important to realize that once the electronic charge is factored out and the charge is interpreted in terms of the fractional spin $e^2/$c the paradox discussed in the Appendix F of [18] disappears: the apparent paradox relates with the distinction between mechanical action as a one-dimensional period and electromagnetic action to be a three-dimensional period. In the case of photon we have one-dimensional period integral Eq. (18) reminding us the Bohr-Sommerfeld quantization. Moreover the generalized momentum of a charged particle in the presence of electromagnetic field becomes $\mathbf{p} - \alpha\mathbf{a}$ where α is the fine structure constant $e^2/\hbar c$ that is a dimensionless number. Eq. (18) as a one-dimensional period integral is consistent with the momentum integral. Post remarks on Aharonov-Bohm effect in his book [2] and connects it with the flux quantization in a superconductor. In contrast, here fraction of momentum of photon is carried by the charged particle.

The nature of the underlying manifold is a delicate issue because the conventional electrodynamics in four-diomensional space-time with a pair two-form F (of fields **E** and **B**), impair two-form (of fields **D** and **H**), and the current density three-form does not retain metric-free topological invariance as noted by Birss [19]. In three-dimensional space it is possible to have

a metric independence. The things are somewhat different in our approach as one-form is fundamental; however time has twin roles. There is a closed periodicity corresponding to internal rotation, and an open usual time coordinate corresponding to the external translational motion of photon. It is expected that the scalar potential would represent the energy, but it would be a zero-form.

How do we represent spin and translational energy of photon? Note that translational periodicity gives rise to a sort of propagating harmonic wave, and there is no potential energy. We propose that the total energy is equally divided into spin energy and translational energy i.e.

$$h\nu = \hbar\omega/2 + h\nu/2 \tag{19}$$

It is interesting to draw an analogy with a classical particle having momentum p, linear velocity v, angular momentum L and angular velocity ω then the kinetic and rotational energies are pv/2 and Lω/2. If we let v=c, p=$h\nu$ /c and L =$\hbar$ we get back Eq. (19). It is at present not clear to me if we can obtain this result from the topological arguments.

In this picture electromagnetic field is some kind of a photon fluid, therefore at least one additional scalar field is needed to describe photon number density. Eq. (18) indicates that magnetic field vector corresponding to **a** (multiplied by number density) would correspond to angular momentum flux, and total angular momentum would comprise of spin (topological) part and orbital part. One of the Maxwell field equations

$$\nabla.\mathbf{B} = 0 \tag{20}$$

implies that $\mathbf{B} = \nabla \times \mathbf{A}$, and therefore, for pure gauge field $\mathbf{A}$ equal to the gradient of a scalar field, $\mathbf{B}$ is zero. In the unit of $\hbar$, let us denote the magnetic field by $\mathbf{b}$, then we have

$$\int \mathbf{b}.d\mathbf{S} = \mathbf{L} + \mathbf{S} \tag{21}$$

in the present interpretation. What does the electric field $\mathbf{e}$ represent? Noting that the electromagnetic field tensor is a second rank antisymmetric tensor, and the interpretation of $\mathbf{b}$ as angular momentum vector we have argued [4] that the field tensor be interpreted as angular momentum four-tensor. The electric field would correspond to time-space components of the angular momentum four-tensor. In fact, the definition of $\mathbf{E}$

$$\mathbf{E} = -\nabla\phi - \partial\mathbf{A}/\partial(ct) \tag{22}$$

in the standard electromagnetic theory [11] shows that $\mathbf{E}$ is a true vector (changes sign under space reflection or parity), and the peculiar combination of time and space derivatives is not relativistically covariant. Drawing the analogy with the form of the angular momentum four-tensor which has the components [20]

$$M^{0i} = c\Sigma(t\mathbf{p} - Energy\mathbf{r}/c^2) \tag{23}$$

it is proposed that $\mathbf{e}$ represents the motion of the photon fluid as a whole. For details of the conservation law of $M^{\mu\nu}$ for a closed system of particles

$$M^{\mu\nu} = \Sigma(x^\mu p^\nu - x^\nu p^\mu) \tag{24}$$

where summation is over all particles of the system, we refer to [20]

Unlike the interpretation of magnetic field as angular momentum flux of the photon fluid, the electric field vector does not seem to have straightforward physical significance. If $\mathbf{e}$ represents the translation of photon fluid then similar to Eq. (19), for a single photon Eq. (4) could be interpreted as a sum of translational and rotational energy density of the photon fluid. Note the form of the expression of energy for a classical particle

$$Energy = p^2/2m + L^2/2I \tag{25}$$

On the other hand, assuming the definition (22) and noting the interpretation that vector potential and scalar potential represent momentum and energy density respectively the electric field would represent force density.

4 Black-Body Radiation

Planck's second theory gave statistical origin of the zero-point energy, and in modern theories it is a typical quantum effect. Eq. (19) offers a third origin: $h\nu/2$ energy corresponds to the $h\nu$ /c linear momentum and $\hbar\omega/2$ energy to the spin angular momentum of $\hbar$ for a single photon. In any process that depends only on the momentum exchange the energy for a photon has to be taken $h\nu$ /2 not $h\nu$ as is done conventionally. Though black-body radiation law is well established, we revisit it in the light of our hypothesis. It is significant that Boyer [21] has given four derivations of the radiation law, and in each of them zero-point radiation plays a crucial role. In his approach the zero-point radiation is a random classical radiation. If 'quantum ideas' means discreteness then our approach belongs to extreme quantum domain

since space itself is discretized; however it has nothing to do with the standard quantum theory.

In all derivations momentum exchange is the key process for attaining thermodynamical equilibrium. Whether one is considering classical radiation or one is considering light quantum, factor of 2 in essence arises due to the polarization states. Bose calculates phase space volume and multiplies it by 2 to account for two polarization states of photon. Let us consider Eq. (19) then the first expected change would be that for momentum $h\nu/$c for a photon we have to take energy $h\nu/2$. Retaining other assumptions made by Bose the final result for the energy density $u(\nu)d\nu$ within the frequency interval $d\nu$ is given by

$$u(\nu)d\nu = (h\nu/2)\frac{8\pi\nu^2 d\nu}{c^3(e^{h\nu/2kT} - 1)} \tag{26}$$

It is easy to show that for small ν this expression goes over to the Rayleigh-Jeans law. Integrating over all frequencies it can be verified that the total energy density satisfies the Stefan-Boltzmann law. However there is something amiss here as Eq. (26) does not agree with the Planck's formula.

An important characteristic of black-body radiation is that it is unpolarized. Recently the nature of unpolarized light has been the subject of renewed significance, see Lehner et al [22] for a critical discussion and review. Assuming spin or polarization correlated photon pairs such that each single object (i.e. the pair) has spin zero, the ensemble of these pairs would certainly be unpolarized. If in the thermodynamical equilibrium of the black-body radiation photon pairs are assumed to be the basic entities in the momentum exchange process then the corresponding energy becomes hν, and the multiplication by 2 gets added significance counting two photons with opposite spin in the pair. Obviously the Planck's formula is recovered with a new interpretation. Mandel and Wolf [14] discuss polarization using the coherence matrix, and show that for each propagation vector the black-body radiation is unpolarized. Pairs of photons with given momentum as proposed by us are also unpolarized. Taking note of the characteristic polarization entangled states for which each one of the photons is unpolarized [14], it is possible that in the black-body radiation the photon pairs at the source are generated in polarization correlated states.

Note that spin energy has not entered into the discussion of the Planck's law: is there no role of this dormant energy? A careful reflection shows that

at absolute temperature zero, the zero-point radiation spectrum has a plausible origin in terms of the spin energy $\hbar\omega/2$ of photons with momentum in a sort of frozen state resembling with that of Bose-Einstein condensate which is a zero momentum state. Besides this we envisage the possibility of imparting rotation to small particles suspended in the black-body radiation enclosure in which polarized light beams are injected from outside source. Physically one would expect spin energy exchange to contribute in the thermodynamical process in this modified black-body enclosure of mixed i.e. unpolarized+polarized radiation.

5 Conclusion

I have been investigating the well known foundational problems of electrodynamics for past more than two decades which have defied satisfactory solution in spite of the great efforts put by e minent physicists; the present paper is a contribution in this continuing process of my understanding. The main results of the present work are the definitive interpretation of magnetic field as angular momentum flux, the hypothesis that the total energy of a single photon is equally divided into kinetic and spin parts, and the new insight gained from the black-body radiation formula using a radically different interpretation of zero-point energy.

Some of the arguments are still tentative, and the inconclusive interpretation of the electric field is unsatisfactory. In a complete theory it is expected that electric field and the Maxwell equations would emerge from photon fluid dynamics representing the property of the fluid. Two options to tackle this problem are being explored: (1) assuming the analogy with the rotating superfluid and treating photons as vortices, the microscopic theory of superfluidity could be applied to the photon fluid case, and (2) since photon is proposed to be a space-time structure, the abstract space-time flow of null lines in a geometrical framework offers another approach. In the curved space-time geometry there is an important result: null lines are subjected to vorticity and shear. The flow of null vector lines gets separation and expansion as a geometrical effect. Since physically photon trajectory is a null line, and Maxwell field equations satisfy general covariance, geometry and topology of space-time could throw some light on developing the photon fluid paradigm for electromagnetism.

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